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# Statistic Strategy of Damage Detection for Composite Structure Using the Correlation Function Amplitude Vector

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## Abstract

A statistic method of damage detection based on the Correlation function amplitude Vector (CorV) is proposed to detect local delamination damage of composite structures. In the numerical simulation, finite element models of cantilevered composite laminates for the pre-damage state and post-damage state are firstly established and local delamination damage is simulated, which aims to fetching the acceleration responses signals under concentrated steady random excitation imposed on each of them. Then different nodes are used as the reference points in each CorV calculation for statistic evaluation. The Correlation function amplitude Vector Assurance Criterion (CVAC) is adopted as the damage extent indicator. And the relative changes between the CorVs of the intact and damaged laminate are utilized to determine the delamination damage area roughly. Combined with a statistic evaluation formula, the precise damage can be finally located. The effectiveness and robustness of the proposed statistic detection approach are verified by the damage detection examples for single-damage and multiple-damage detection as well as an experiment on a composite honeycomb sandwich beam with prefab debonding damage, respectively.

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**Keywords:** correlation function amplitude vector (CorV); composite structure; damage detection; random excitation; statistic detection

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## 1. Introduction

Structural Health Monitoring (SHM) has great significance in many engineering applications, such as enhancing the structure safety, forecasting structure failure, reducing the cost of structure maintenance and improving

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productive efficiency. Structural damage detection is the key point of SHM. Among the damage detection techniques, the methods based on time domain vibration response have received increasing attentions of researchers due to its advantages of only requiring analyzing and comparing the vibration response signals to detect damages without modal parameter identification or finite element modeling for the structures. Modal parameters usually can't be identified precisely in practice and in many cases inaccurate finite element model may be obtained by inadequate assumptions and simplifications. In the damage detecting techniques which adopt only the time domain vibration response, many kinds of signal processing techniques, such as wavelet transform and HHT (Hilbert-Huang Transform), are utilized to extract damage indices[1~3]. E. Douka et al. propose a simple method for beam like structures based on wavelet analysis [4]. The fundamental vibration mode of the beam is analyzed by continuous wavelet transform. The location and size of the crack are determined and even the depth can be estimated. Further study on a double-cracked beam is complicated in reference [5] by the same approach. A.V. Ovanesova and L.E. Suárez perform the wavelet transform on the response signal obtained from frame structures under static or dynamic loads to locate the crack damage [6]. Darryll Pines and Liming Salvino[7] combine empirical mode decomposition (EMD) with the Hilber Transform to track unique features in the vibratory response of structures. A damage detection method using HHT is verified numerically by a model of wing box [8]. However, boundary distortion often occurs in performing the wavelet transform and the end effect of EMD also needs to be handled. In addition, fake intrinsic mode function (IMF) usually can't be identified successfully. Some other candidate methods based on signal processing are also investigated to obtain the damage indicator. For example, difference between the energy of response signals of the intact and damaged structure can be employed as the damage index [9]. In this method the maximum value in the energy difference vector corresponds to damage location. Moreover, statistic technique and singular value decomposition, etc. are also employed in damage detection [10~11]. In most of the mentioned methods above, the response signals are obtained by imposing deterministic excitation on the structure. In practice, however, structures are subject to environmental excitation, so an on-line damage detection technique is desirable. In 2007, Yang proposed a new damage detection method by using correlation function amplitude vector (CorV) of the vibration response of structure as damage index. It is proved that the CorV of a structure is related to the frequency response function (FRF) of the structure under a steady random excitation with a specific frequency spectrum. The change between the CorVs of the intact and damaged structure can be used as the damage index. The capability of this new damage detection method is verified by numerical simulations and experiments [12], which demonstrated the feasibility of damage detection using the time domain vibration responses under ambient excitation.

It is well known that composite materials are more and more extensively used in engineering fields with its advantages of low weight, high specific stiffness, excellent fatigue and corrosion resistance etc. compared with the conventional metal alloy materials. Composite structures especially composite laminated structures, however, are prone to be damaged in the form of delamination, fiber breakage and matrix cracking in their manufacturing and service processes and these damages are often invisible. Such damages in composite structure will lead to abrupt failure without early warnings. Thus damage detection for composite laminate structures has become the hot issue in the field of structural health monitoring. A review about model dependent delamination detection method in composite structures is summarized in [13]. Pizhong Qiao et al. investigate an E-glass/epoxy composite plate with an embedded delamination using two different actuator-sensor systems [14]. Curvature mode shapes and uniform load surface curvatures are analyzed by three damage detection algorithms. However, mode shapes need to be identified firstly. B. Whittingham et al. conduct experiments on adhesively bonded GFRP composite beam and T-joint specimens to detect delamination and finally found that frequency response shifts noticeably from the FRF of the intact structure with the increasing of delamination size [15]. They also found that when the actuator and sensor are both near the damaged area additional peaks will appear due to the secondary vibrations within the delaminated section. Therefore, an extensive optimized actuator/sensor network is required to distribute over a large structure in order to locate the damage. L.H. Yam et al. combine wavelet package with artificial neural network (ANN) to detect crack damage in a PVC sandwich plates [16]. Later verification is conducted by L. Yu et al. on static laminated composite shells partially filled with fluid [17]. The main drawback of ANN method is the need of large numbers of training samples, which is time-consuming.

In the present work, the CorV method is extended to the damage detection in composite structures and a statistic strategy is proposed to improve the identification precision for delamination damage of composite laminated structures. Numerical simulation is performed to localize the delamination damage of a cantilevered composite

laminates. No modal parameters are required in the whole procedure. The results show the validity of the proposed approach to detect delamination damage for both single damaged and multiple damaged laminate structures.

## 2. The principle of CorV method

The cross correlation function is a measure of the correlation between two signals. For a structure under a steady random excitation with  $n$  response-measuring nodes, the cross correlation function between the response of the  $k$ -th node  $x_k(t)$  and the response of the  $l$ -th node  $x_l(t)$  is given by

$$R_{kl}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x_k(t) x_l(t + \tau) dt \quad (1)$$

Let node  $k$  be the reference point, and denoting  $\max |R_{kl}(t)| = |R_{kl}(\tau_l)| = r_{kl}$ . Calculating the cross correlation function between  $x_k(t)$  and  $x_l(t)$  ( $l=1, 2, 3, \dots, n$ ), respectively, and each  $r_{kl}$  can be obtained to form the cross correlation function amplitude vector can then be established as follows:

$$\mathbf{CorV}_k = \{r_{k1} \ r_{k2} \ r_{k3} \ \dots \ r_{kn}\} \quad (2)$$

In fact, the measured responses  $x_k(t)$  and  $x_l(t)$  are two samples of the ergodic stochastic process. Thus the expectation of  $x_k(t) x_l(t + \tau)$  within the recording period  $T$  is given by

$$\begin{aligned} R_{kl}(\tau) &= E[x_k(t) x_l(t + \tau)] \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \lim_{T \rightarrow \infty} E \left[ \frac{1}{T} X_k^*(\omega) X_l(\omega) \right] e^{i\omega\tau} d\omega \end{aligned} \quad (3)$$

$X_k(\omega)$  and  $X_l(\omega)$  are the Fourier transform (FT) of  $x_k(t)$  and  $x_l(t)$ , respectively.

The FT of excitation vector  $\{f(t)\}$  is:

$$\mathbf{F}(\omega) = \{F_1(\omega) \ F_2(\omega) \ \dots \ F_n(\omega)\}^T \quad (4)$$

The  $j$ -th row of FRF matrix is:

$$\mathbf{H}_j(\omega) = \{H_{j1}(\omega) \ H_{j2}(\omega) \ \dots \ H_{jn}(\omega)\} \quad (5)$$

Then  $X_k(\omega)$  and  $X_l(\omega)$  can be rewritten as

$$\begin{cases} X_k(\omega) = \mathbf{H}_k(\omega) \mathbf{F}(\omega) \\ X_l(\omega) = \mathbf{H}_l(\omega) \mathbf{F}(\omega) \end{cases} \quad (6)$$

Substituting Eq. (6) into Eq. (3), at  $\tau = \tau_l$  the cross correlation function between  $x_k(t)$  and  $x_l(t)$  can be achieved by

$$r_{kl} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \lim_{T \rightarrow \infty} E \left\{ \frac{1}{T} [\mathbf{H}_k(\omega) \mathbf{F}(\omega)]^* \cdot \mathbf{H}_l(\omega) \mathbf{F}(\omega) \right\} e^{i\omega\tau_l} d\omega \quad (7)$$

From Eq. (7), it is known that  $r_{kl}$  ( $l=1,2,3,\dots,n$ ) only depends on the FRF matrix of the structure if the time delay  $\tau_l$  is kept constant and the CorV have a specific shape corresponding to the specific excitation  $F(\omega)$ . In other words, the CorV of the structure is only determined by the frequency response function matrix when the structure subject to a steady random excitation with a specific frequency spectrum. If damage occurs in a structure, difference

will be exhibit between the FRF matrices of the intact and damaged structures .Thus this difference can be identified by comparing the CorVs of the intact and damaged structures.

Note that the CorV is a vector, so it can be normalized for explicit comparison. The normalized CorV is defined by:

$$\overline{\text{CorV}(i)} = \frac{\text{CorV}(i)}{\left[\sum \text{CorV}^2(j)\right]^{\frac{1}{2}}} \quad (8)$$

The normalized CorV referred in the following text will still be denoted as CorV for simplicity. The relative change between the intact and damaged laminate structure can be defined by

$$E_{CV}(k) = \frac{\text{CorV}_k^d - \text{CorV}_k^u}{\text{CorV}_k^u} \times 100\% \quad (9)$$

$\text{CorV}_k^d$  and  $\text{CorV}_k^u$  refer to the CorV of the intact and damaged structure respectively using k-th node as the reference point. At the nodes close to the damaged area the introduced damage index  $E_{CV}$  will be larger than the index for the nodes which are far from the damaged zone. Therefore  $E_{CV}$  can be used as the index to locate the damage. The damage location is assessed by the maximum absolute value in  $E_{CV}$ .

In order to quantify the damage explicitly, an induced measure CVAC is introduced which is defined as a criterion for the correlation between two CorV vectors:

$$\text{CVAC} = \frac{\left[\sum \text{CorV}(j)\text{CorV}^*(j)\right]^2}{\sum [\text{CorV}(j)]^2 \sum [\text{CorV}^*(j)]^2} \quad (10)$$

where  $\text{CVAC} \in [0,1]$ , CorV and CorV\* are calculated using the vibration responses of the intact structure and the structure to be detected. As mentioned above, the structure will be excited with excitations with the same spectrum in these two states. It is clear that if the structure to be detected is intact, the CVAC must be equal to 1. Obviously, the smaller the CVAC, the weaker the correlation of the CorVs, hence the damage severity can be estimated.

### 3. Damage detection examples

#### 3.1. Damage simulation of composite laminate plate

To demonstrate the capability of the proposed technique, a cantilevered composite laminate plate with dimensions 800mm×500mm is considered for damage identification studies. The material parameters are listed in Table 1. The finite element model (FEM) consists of 20×15 elements meshed with 4-node quadrilateral shell element in the MSC.Patran software and the vibration responses are calculated to obtain the required signals for damage detection. The composite laminate is laminated by  $[0^\circ/45^\circ/-45^\circ/0^\circ/90^\circ/0^\circ]$  s using T300/QY8911 carbon-fiber and the thickness of each layer is 0.15mm. Figure 1 illustrates the FEM of the laminate and part of the element labels are also shown in this figure.

Table 1. Material parameters of T300/QY8911

$E_1$ /GPa	$E_2$ /GPa	$G_{12}$ /GPa	$\nu_{21}$	$\rho$ / (kg/m <sup>3</sup> )
135	8.8	4.5	0.33	1610

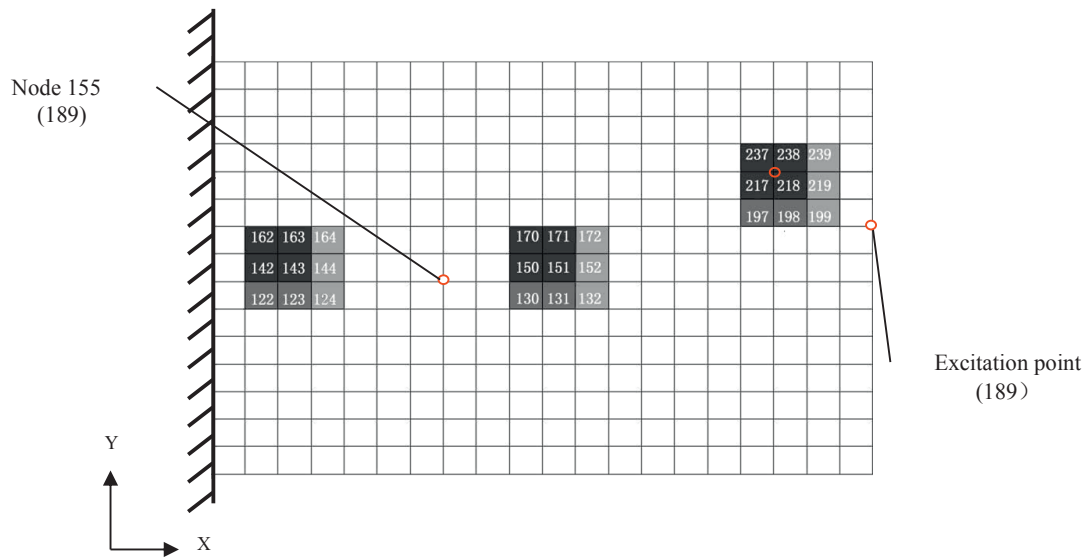


Fig. 1. Finite element model of the cantilevered composite laminate

It's supposed herein that the delamination occurs at the midplane of the composite laminate. The intact laminate is laminated by  $[0^\circ/45^\circ/-45^\circ/0^\circ/90^\circ/0^\circ]$  s with a total thickness of 1.8mm. The delamination damage is simulated in the software MSC.Patran as follows: taking the elements 217, 218, 237, 238 for example, copy these elements at the original position; then, merge the surrounding nodes and the two nodes in the center of the region are relaxed; finally the stacking properties  $[0^\circ/90^\circ/0^\circ/-45^\circ/45^\circ/0^\circ]$  and  $[0^\circ/45^\circ/-45^\circ/0^\circ/90^\circ/0^\circ]$  are assigned to each half laminate respectively while the property of  $[0^\circ/45^\circ/-45^\circ/0^\circ/90^\circ/0^\circ]$  s is assigned to the un-delaminated region.

### 3.2. Damage detection by *CorV*

The following two types of damage cases are considered for this study: (i) single damage induced at three locations ;(ii) multiple damage induced at three locations with the same levels of severity of case (i).

#### 3.2.1. Damage detection for single damage cases

Some single damage cases for three typical different positions of the cantilevered laminate are simulated respectively in order to verify the feasibility of the proposed method for detecting damages at different positions. Table 2 gives the details of the damage scenarios and the damage areas are also shown in Fig. 1.

Table 2. single-damage cases for the laminate

position	near the root of the laminate			at the center of the laminate			near the tip of the laminate		
Damage case	1	2	3	4	5	6	7	8	9
Damaged element label	142,143	122,123	122~124	150,151	130,131	130~132	217,218	197,198	197~199
	162,163	142,143	142~144	170,171	150,151	150~152	237,238	217,218	217~219
		162,163	162~164		170,171	170~172		197,198	237~239

Considering that accelerometers are usually used in vibration tests, in the simulation of this work, the acceleration responses of the intact and damaged laminate are used to feature the damage index. The intact and damaged laminate are excited by the steady random excitation with a frequency bandwidth of 15~25Hz at node 189. The acceleration

responses are calculated at each of the simulated response measurement grid points by modal superposition approach. A sampling period of 10 s, ITS values of 0.002s, and a sampling frequency of 500 Hz is used to obtain 5001 samples at each measurement grid point (all nodes of the FE mesh). In the calculation Rayleigh damping assumption is adopted with the coefficients of 0.05 and 0.06 for the intact and damaged laminates, respectively. This is because delamination increases damping of structure.

After obtaining the acceleration responses at all the nodes of the laminate, choose any node (e.g. node 155) as the reference point to calculate CorV. Figure 2 shows the CorVs of the intact and damaged laminates for damage case 7.

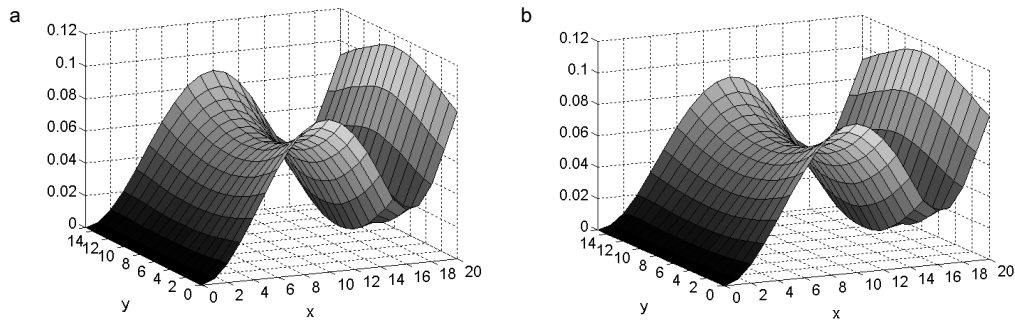


Fig. 2 (a) CorV of the intact cantilevered laminate; (b) CorV of the damaged cantilevered laminate case 7.

In order to investigate the consistency of CorV of the laminate under two random excitation samples which have the same frequency bandwidth and similar power spectral density (PSD), the CVAC between two CorVs obtained by responses of the intact laminate excited by such two excitation samples respectively is calculated and gives the result of 0.999999998. It is clear that the excitation can be sampled with the same frequency bandwidth and similar PSD to obtain the CorVs of the structure. The CVACs for 3 different single damage cases are listed in Table 3.

Table 3. CVAC value for the intact and damaged laminate with single damage

position	near the root of the laminate			at the center of the laminate			near the tip of the laminate		
Damage case	1	2	3	4	5	6	7	8	9
amount of damaged elements	4	6	9	4	6	9	4	6	9
CVAC	0.99992	0.99992	0.99982	0.99965	0.99929	0.99821	0.99999	0.99997	0.99991

It's found that the CVAC for the damaged laminate is far smaller than that for the intact laminate (see Table 3). CVAC can be adopted as index to identify the damages of different damage extents at the three different positions. In addition, CVAC also decreases monotonously with the expanding of delamination region. Therefore, CVAC can quantify the relative damage extent of the laminate.

### 3.2.2. Damage location

Equation (10) shows that CVAC is just a scalar quantity but not a function of position, so it only can be used to assess the damage extent rather than damage location. An index is proposed to locate the damage. For the structures with tiny damage, there is no obvious difference between the CorVs of the intact and damaged laminate apparently (see Fig. 2). However, the damaged laminate contains the damage information as a result of the stiffness loss due to local delamination. Local damage will affect the dynamic behavior of the whole structure to a certain degree. It results in reduction of natural frequencies and changes in mode shapes of vibration. So the analysis of these changes makes it possible to identify damage. As mentioned in section 3.2.1, when the excitation has same frequency

bandwidth and similar PSD, CorV of the structure will present a specific shape. Therefore,  $E_{CV}$  which is the relative change between the CorVs of the intact and damaged laminate is proposed to detect damage as the damage indicator. Take damage near the tip of the laminate for example, the detection procedure for 4-element damage, i.e. damage case 7 is as follows:

Choose any node as the reference point and calculate the CorVs of the intact and damaged laminate, as shown in Fig. 2. According to Eq (9)  $E_{CV}$  is obtained by calculating the relative change between the CorVs of the intact and damaged laminate. As shown in Fig. 3 (a) in which the darker the color of the element the higher the  $E_{CV}$  value. It can be seen that, the damage position along Y axis is located almost correctly (row 11-13), while the position along X axis has a little shift from the actual location. The damage will be located more accurately with the increasing of the grid density in simulation or the measure point in practice. Besides, it can be observed that the delamination region involves 4 elements. When the delamination region extends to 6-element, e.g. case 8, the identification result illustrated in Fig. 3 (b) is obtained using the same approach. It can be observed that location region enlarges accordingly compared with 4-element damage case. So the delamination region can be estimated by  $E_{CV}$ . In addition, the maximum value of  $E_{CV}$  increases with the increase of delamination size.

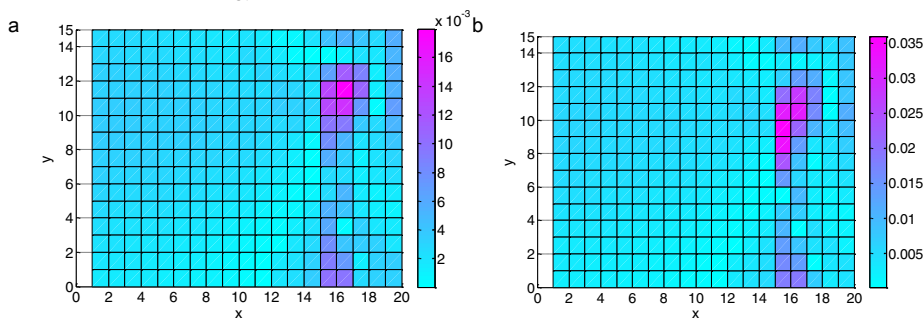


Fig. 3 Identification result of damage location: (a) case 7 ;(b) case 8.

Consider the damage cases at the other two positions of the laminate which both involve 4 elements, e.g. damage case 1 and case 4. At first, choose one node as the reference point to identify damage following the detection procedure as that for case 7 and the identification results is shown in Figure 4. It can be seen that for the single damage cases near the root and center of the laminate, the damages also can be identified and located correctly. The highest peak is generated at the actual damage location for both cases. For case 4 there are still some additional much lower peaks at other local areas comparing with the highest peak. Besides it's can be seen that the level of alteration of the CorVs as a result of delamination is dissimilar for different damage location.

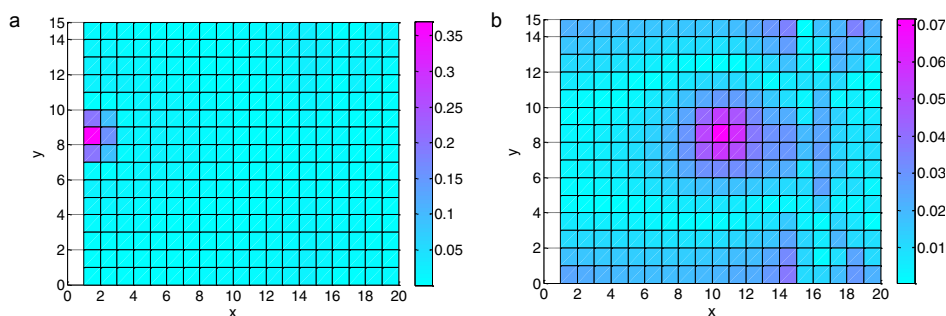


Fig. 4 Identification results of damage location using node 155 as the reference point:(a) case 1;(b) case4.

It's well known that damages at different positions have varying effect on the dynamic characters of the structure. Damage closer to the root of the cantilevered laminate has more significant effect on the dynamic properties of the structure, so the relative change of the CorVs between the intact and damaged structure namely  $E_{CV}$  for case 1 is



the most evident compared with cases 4 and 7, as shown in Figs. 3 and 5. With the damage closer to the tip of the laminate, the maximum value of  $\mathbf{E}_{CV}$  decreases.

It should be noted that the above described is the damage detection procedure using one node as the reference point, which made damage detection potentially inaccurate because in actual damage detecting, not every node can be served as the reference point to detect and locate the damage correctly. Therefore, it's necessary to examine the multiple nodes as the reference points to facilitate accurate damage diagnosis and a statistic evaluation procedure should be incorporated to obtain the reliable results. The scheme of this statistic damage detection is described as follows: calculate the CorVs of the intact and damaged structure using each node of the FEM of the laminate as the reference point in turn; then calculate the damage index  $\mathbf{E}_{CV}$ s; a group of location results which correspond to the maximum value of each  $\mathbf{E}_{CV}$  are finally obtained; together with a statistic evaluation, the result corresponding to the highest evaluation index is the most possible damage region. The evaluation index is defined by:

$$P(x, y) = \frac{N(\hat{x}, \hat{y})}{N_{total}} \times 100\% \quad (x = 0, 1, \dots, 20, x \in Z; y = 0, 1, \dots, 15, y \in Z) \quad (11)$$

Where  $\{(\hat{x}, \hat{y}) | \hat{x} \in [x - \delta, x + \delta], \hat{y} \in [y - \delta, y + \delta], \delta \in N\}$  define a square region,  $N(\hat{x}, \hat{y})$  is the number of the identifying results falling into the defined region,  $(x, y)$  is the node coordinate in Fig. 1.  $N_{total}$  is total identifying times which is equal to the number of reference points. Integer  $\delta$  is offset of the node coordinate denoting the extent of influence of delamination region. With the increasing of the grid density and the decrease of  $\delta$ , the damage will be located more accurately. In this work,  $\delta$  is set to 1.

Table 4 shows the identification results when using all the nodes of the FEM in the detecting procedure. Numbers in the third and fourth rows of the table are the element labels. For the three types of delamination damage as mentioned above, it can be seen that the identification results which correspond to the highest statistic evaluation index are in accord with the actual damage regions excellently. It's obvious that the proposed method has good capability of damage locating for the simulated single damage cases.

Table 4. Identification results for 4-element-delamination cases using different nodes as reference points

Damage case	1	4	7
highest statistic evaluation index	100%	93.75%	100%
Location result	142,143	150,151	217,218
	162,163	170,171	237,238
Actual delamination region	142,143	150,151	217,218
	162,163	170,171	237,238

With the damage closer to the root of the cantilevered laminate, the damage has increasingly serious effect on the dynamic properties of the structure. Hence this kind of damage can be located more easily by the change of CorVs before and after the damage occurs. On the contrary, it's difficult to detect damage closer to the tip of the cantilevered laminate.

Another 4-element delamination case which is the dashed circle surrounded region denoted in Fig. 5 is also simulated to prove the deduction further and node 155 is also used the reference point in the calculation of CorV. As shown in Fig. 5, the maximum value of  $\mathbf{E}_{CV}$  occur at the top right corner of the laminate, which lead to misdiagnose. Thus, for the damage on the edge of the laminate, the proposed method can't locate damage precisely due to the slight effect of the edge damage on the global dynamics characters of the structure.



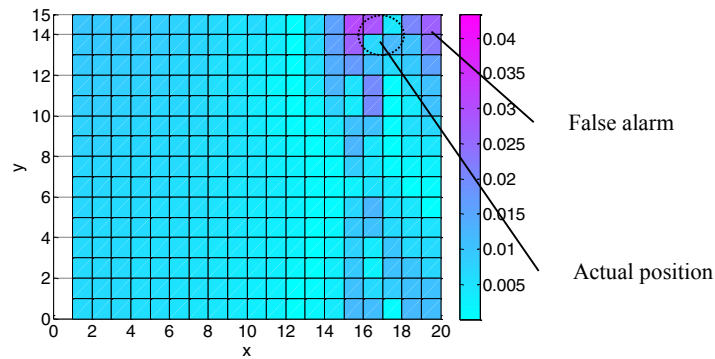


Fig. 5. Identification results of the laminate with a damage on its fringe

### 3.2.3. Damage detection for multiple damage cases

Multiple damages may occur in engineering practice, while few effective damage detection methods are developed at present. The damage index proposed in this study is based on the change of CorVs of the intact and damaged laminate. When the laminate is damaged, CorV will change at positions corresponding to the delamination region, so this method is used to explore the possibility of identifying and locating the multiple damages.

To verify this capability for multiple damage detection, several cases of 4-elements damage at two different positions of the laminate are simulated, as presented in Table 5. The excitation is absolutely the same as that in section 3.2.2. The detection results are illustrated in Fig. 6.

Table 5. Cases of two damages for the laminate

Damage case	10	11	12
Damaged element label	[142, 143, 162, 163] [150, 151, 170, 171]	[142, 143, 162, 163] [217, 218, 238, 239]	[150, 151, 170, 171] [217, 218, 238, 239]

It can be observed in Figs. 6 (a), (b) and (c) that although the simulated delamination regions are of the same size, the  $E_{CV}$  near the root of the laminate is much higher than the values at the other two damage positions which even have fallen into oblivion in the plot. This is because damage near the root of the laminate is strongly sensitive to the dynamic characters of the structure compared with the damage of the same size at the other two positions. But this error doesn't contradict with the actual engineering problem. As we know, damages near the root of the cantilevered structure often lead to the most severe case. In case 10, the maximum value of  $E_{CV}$  locates at the position which is the intersection of the 9th row and 1st column of the elements, and the second maximum value locates at the intersection of the 9th row and 11th column. For convenience of observation, plot the  $E_{CV}$  s near the position which has the second maximum value, as shown in (b). The damage in the center of the laminate can be identified clearly. The plots of  $E_{CV}$  for the other two cases are processed in the same way, as shown in Figs. 6 (d) and (f). The two damage positions are both identified for each case. In addition, for damage case 12, boundary effect is evident. Some additional peaks are also observed on the edge of the laminate.

In comparison with Table 5 the identification results which correspond to the highest statistic evaluation index are also consistent with the actual simulated delamination regions, as presented in Table 6. It's obvious that for all the three multiple damage cases the damage detection approach presents the nice validity.

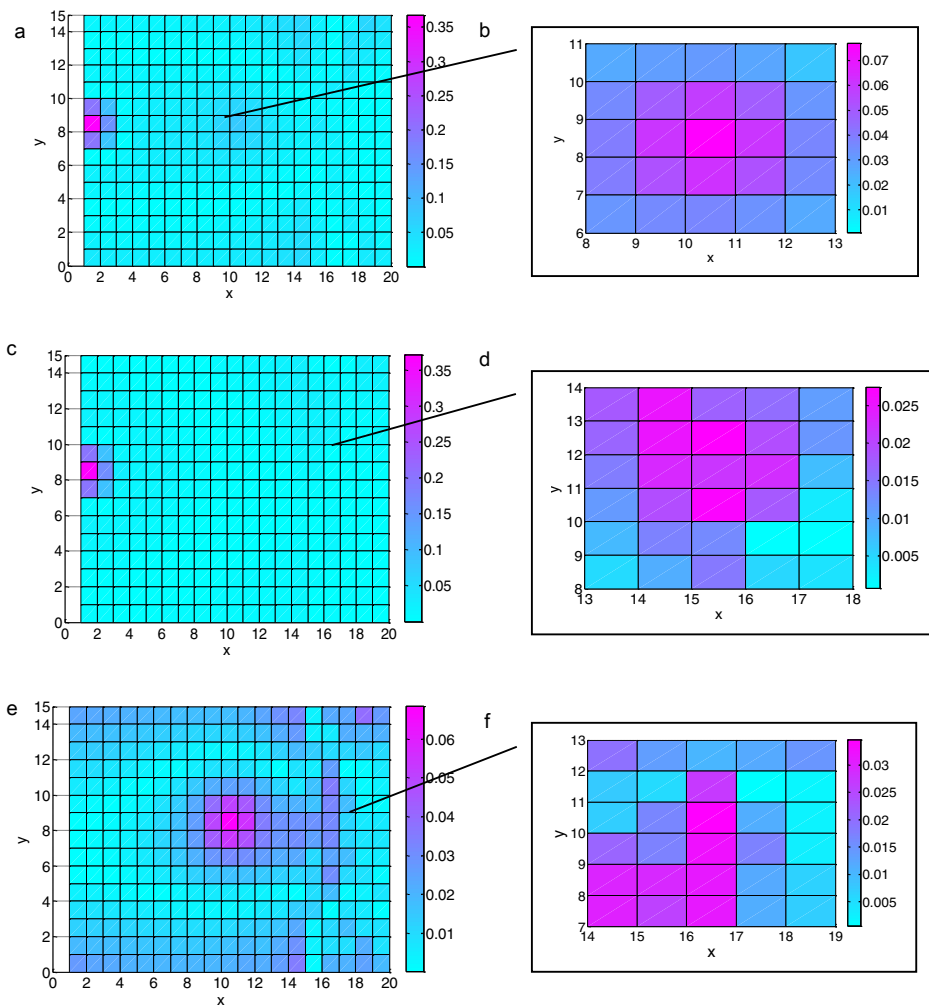


Fig. 6. Identification results of damage location for the two damage cases:(a) Identification result for damage case 10;(b) zoom-in plot of (a);(c) Identification result for damage case 11;(d) zoom-in plot of (c);(e) Identification result for damage case 12;(f) zoom-in plot of (e).

Table 6. Identification results for the double-delaminated laminate using different nodes as reference points

Damage case	10	11	12
highest statistic evaluation index	90%	80%	80.31%

### 3.2.4. Experiment validation

In this section the method is adopted to detect the debonding damage of composite sandwich beams.

The dimension of the test specimen is 55cm×4cm×1.6cm, as shown in Fig.7. The corn is made of hexagon aluminum honeycomb and the facing is made of carbon fibre. The stacking sequence of the facing is  $[90^\circ/0^\circ/90^\circ/0^\circ]$ . 10 PCB333B30 accelerometers are bonded on the beam with identical interval. An artificial law with the size of 4cm×3cm is manufactured near the root of the beam with a thin knife to simulate the debonding damage, as shown in Fig.7.(b) and Fig.8.(a).

In both cases, the honeycomb sandwich beam is excited by the actuator YE15401 with frequency bandwidth of 0~100Hz at the free end of the beam and the acceleration response of each measuring point is recorded, as shown in

Fig.8.(b).The first natural frequency of the intact beam is 52.196Hz. The CorVs of the intact and damaged beams are calculated respectively, as shown in Fig.9. (a) and (b). Fig.9. (c) shows the identification result using measure point 4 as the reference point. The maximum value of  $E_{CV}$  locates at the debonding region. When using different measure point as the reference point, the maximum values of  $E_{CV}$  s all locate at the debonding region. It can be seen the CorV-based structural damage detection method can be utilized to correctly locate the debonding damage location in the composite honeycomb sandwich beams, in other words, the highest statistic evaluation index is 100%.

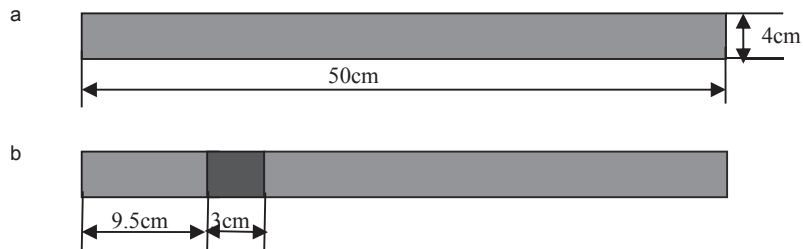


Fig. 7. Test specimens: (a) Intact beam; (b) damaged beam.

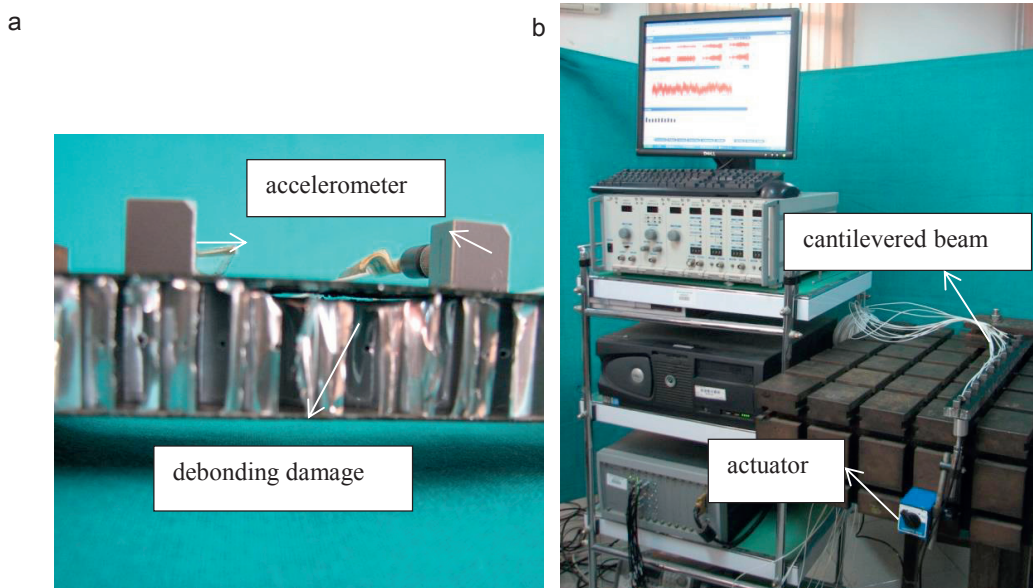


Fig. 8. Experiment setup and detail of debonding in honeycomb sandwich beam: (a) test setup; (b) debonding damage.

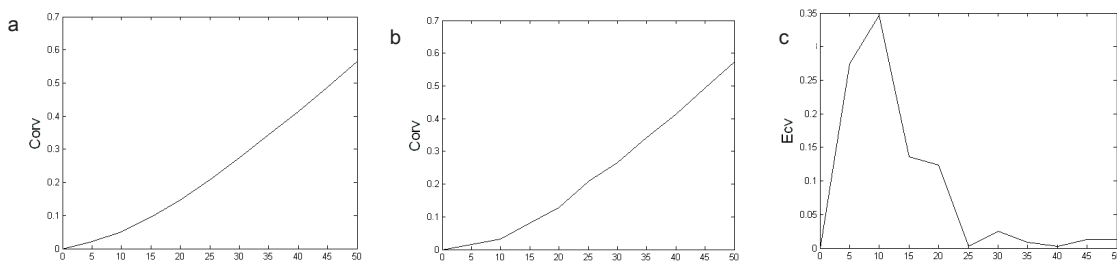


Fig. 9. (a) CorV of the intact beam; (b) CorV of the intact beam; (c) Identification result.

#### 4. Conclusions

Damage detection simulations are performed on a cantilevered composite laminate based on the CorV under random excitation. The FEM of the laminate is established and delamination damages are simulated. The index  $E_{CV}$  which is the relative change between CorVs of the intact and damaged laminate is calculated for damage location. A statistic detection method is proposed and the position with the highest statistically evaluated index is ascertained as the final damage location. In the last section of this paper, a damage detection experiment on a composite honeycomb beam illustrates the feasibility and effectiveness of the method.

CVAC which descends evidently with the presence of delamination can be estimate the relative damage extent. The relative large components of  $E_{CV}$  can be used to determine the delamination region. The proposed method can serve as a method to detect the multiple damages of composite laminate detection and has the feature of anti-noise ability.

With the increasing of grid density of finite element model in the FEM simulations or measuring points in actual damage detections, higher precision of this approach will be achieved. However, the damage detection precision will not be improved when the sensor density reaches a certain extent and in many engineering applications it's impossible to affix many sensors. In addition, how to quantify damage accurately is still a challenging problem. Damage detection of more complicated composite structure need to be further investigated.

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